

Metal-free catalysis of sustainable Friedel–Crafts reactions: direct activation of benzene by carbon nitrides to avoid the use of metal chlorides and halogenated compounds†

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The use of mesoporous graphitic C_3N_4 for the activation of benzene permitted to perform more sustainable Friedel–Crafts reactions by allowing to directly use carboxylic acids, alcohols and even quaternary ammoniums or urea as electrophiles.

Friedel–Crafts reactions are known to be some of the less sustainable industrial processes, producing about 88 mass% of waste, in their standard $AlCl_3$ promoted version.¹ They usually require a more than stoichiometric amount of co-reactant (like $AlCl_3$) and rely on halogenated substrates or anhydrides as electrophiles. Despite their low performances these reactions remain widely used and studied because they are very powerful synthetic tools.² The search for true catalytic Friedel–Crafts reactions has thus attracted a lot of interest. An important step towards greener Friedel–Crafts reactions was achieved by using homogeneous Lewis acidic complexes as “true” catalysts.^{3,4} The current focus on catalysts separation and recycling,⁵ however, has prompted many research groups to look for heterogeneous catalytic systems. Ionic liquids^{6–8} and fluorinated solvents^{9,10} have proved to be suitable green solvents and/or co-reactants for those reactions. Nevertheless, the most promising catalytic systems for Friedel–Crafts reactions are solids, from zeolites to Nafion-functionalised MCM-41s.^{11–14} Besides this issue, the usual electrophiles are rather atom ineffective, which has encouraged the direct use of carboxylic acids for acylation reactions,^{15,16} or alcohols for alkylations.^{17–19} In this contribution, we propose an alternative route for using sustainable electrophiles, such as alcohols, formic acid but also ammonium compounds or urea in Friedel–Crafts type reactions relying on a Lewis basic solid, namely mesoporous graphitic C_3N_4 , **mpg- C_3N_4** , to activate benzene.^{20,21}

A new trend for enhancing heterogeneous catalysis is to maximise the interaction between the active site and the surface of the support.²³ This approach enables us to take advantage of the intrinsic properties of the support for achieving multifunctional catalysis²⁴ or enhancing regioselectivity.²⁵ It can also lead to the discovery of unpredicted catalytic properties of the support itself, as exemplified in the case of zirconium oxide catalyzed

hydroformylation.²⁶ This whole trend may lead to a renewed interest for purely heterogeneous catalysts in fine chemistry. We recently reported the use of a carbon nitride as a metal-free catalyst for Friedel–Crafts acylations,^{20,21} which is in principle strongly related to the above mentioned approach. Among the various possible carbonitride molar compositions, C_3N_4 appeared to be a highly promising material, especially its graphitic allotrope. Kroke *et al.* proposed (and it is now widely admitted) that this material consists of sheets of highly ordered tri-*s*-triazine moieties connected through planarized amino groups as depicted in Fig. 1.²² The synthesis of our catalytic material relied on thermal self-condensation of cyanamide described by Schnick and coworkers.²⁷ Mesoporosity was generated by the use of silica nanoparticles as hard templates. After condensation of the monomers and removal of the template, the resulting powders exhibited specific surface areas ranging from $86 \text{ m}^2 \text{ g}^{-1}$ to $439 \text{ m}^2 \text{ g}^{-1}$ depending on the amount of templating agent. Due to their remarkable electronic properties these solids act as effective Friedel–Crafts catalysts for the acylation of benzene with acyl chlorides. Although the actual active centres (which, for symmetry reasons, could be isolated tri-*s*-triazine units, the combination of the lone pairs of the nitrogens pointing towards the structural holes, *etc.*) are not known yet, the catalysis most probably relies on the activation of the aromatics rather than the activation of the electrophile.^{20,21} Therefore it was assumed that this catalyst could also enable the use of less active and incidentally more sustainable electrophiles.

In this study, the previously described **mpg- C_3N_4** material was used throughout the catalytic experiments. In a typical synthesis, 2.5 g of a 40 wt% water dispersion of 12 nm silica spheres (Ludox[®] HS40, Aldrich) were added dropwise to 1 g of melted cyanamide. The mixture was subsequently heated to $550 \text{ }^\circ\text{C}$ in a closed ceramic crucible for 4 h. The resulting yellow powder was sealed in a quartz

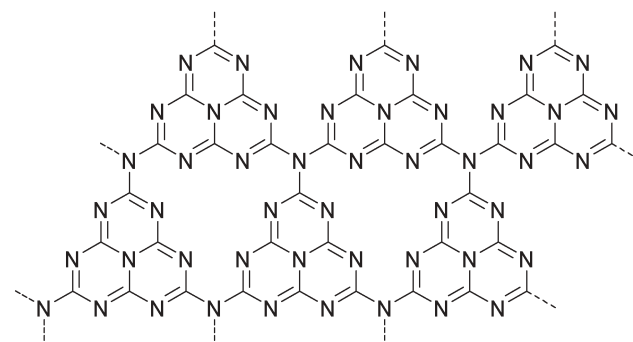


Fig. 1 Structure proposed by Kroke *et al.* for **g- C_3N_4** .²²

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ampoule under vacuum and submitted to an additional heat treatment at 600 °C for 10 h. Chemical removal of the silica by washing with a 4 M NH_4HF_2 solution yielded a mesoporous light brown powder (Fig. 2) exhibiting a surface area of $141 \text{ m}^2 \text{ g}^{-1}$. The pore size distribution was narrow with an average pore size of 12 nm. Small angle X-ray diffraction patterns featured a peak at 0.071 nm, corresponding to a correlation length of 14 nm, which was in good agreement with the pore size determined from BET measurements. The wide angle X-ray diffraction patterns exhibited the typical graphitic interlayer stacking (002) peak of $\text{g-C}_3\text{N}_4$, corresponding to an interlayer distance of $d = 0.319 \text{ nm}$. An intense additional peak is observed at 13.1° , corresponding to an in-plane structural packing motif, namely the hole-to-hole distance of the nitride pores (see Fig. 1). The elemental analysis of the material provided an average atomic C/N ratio value of 0.71 (theoretical value for C_3N_4 : 0.75). The additional small amounts of hydrogen we found (1.5%) were attributed to uncondensed amino functions, adsorbed water and structural defects on the surface. No trace of iron or other transition metals could be detected by Energy Dispersive X-ray analysis (EDX).

The substrates of the catalytic experiments were used without further purification. Benzene was purchased from Aldrich (99.9%, HPLC grade). As electrophiles, three alcohols (methanol 99.9% HPLC grade from Merck, ethanol 99.9% from J. T. Backer, and isopropanol, 99.5% spectrophotometer grade from Aldrich), formic acid (88–91% from Fluka), tetramethylammonium bromide (98% from Aldrich) and urea (99% from Aldrich) were used. In a typical experiment, 50 mg of $\text{mpg-C}_3\text{N}_4$ were placed in a 40 ml stainless steel autoclave fitted with a Teflon mantel (to avoid any contamination by transition metals). As our previous work showed that the solvent could dramatically affect the efficiency of the catalysis two series of tests were undertaken. In the first one the solution placed in the autoclave consisted in 5 ml of the electrophile with 200 mg of benzene (this is the case for methanol, ethanol and isopropanol). In the second one the solution consisted

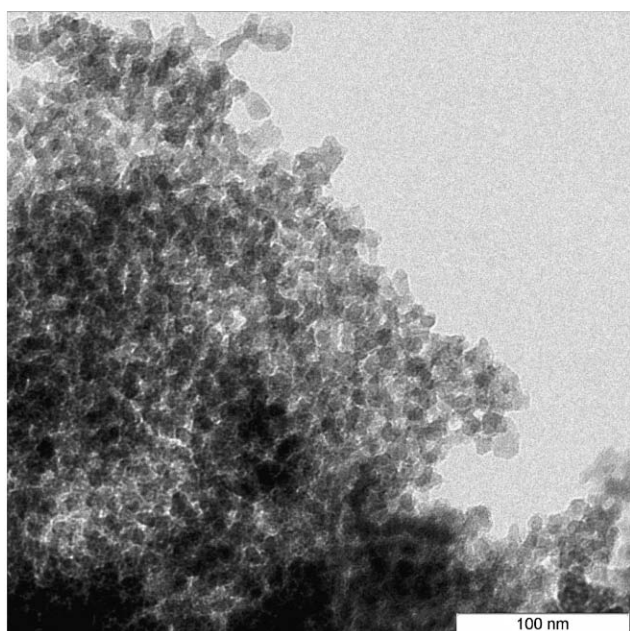


Fig. 2 TEM micrographs of $\text{mpg-C}_3\text{N}_4$.

in 5 ml of benzene with 200 mg of the desired electrophile (methanol, formic acid, tetramethyl ammonium bromide and urea). The closed autoclave was then heated to 150 °C for 24 h. The products of the reaction were analysed and quantified by GC with an internal standard and the products attribution was ascertained by ^1H NMR. The results are summarized in Table 1. The conversion rates indicated in Table 1 were calculated on the basis of the obtained amount of products compared with the initial amount of limiting reactant.

Concerning alkylation reactions with alcohols as reagent, isopropanol yielded 13% of cumene under relatively mild conditions. The current industrial procedure relies on the alkylation of benzene with propene. In that perspective it is important to note that no other product was detected and that the reaction is not entropically disfavoured, which will allow further optimization and high temperature processes. The reaction with ethanol yielded 16% (with respect to benzene) of *p*-diethyl benzene after 24 h. In the case of methanol another situation arose: depending on whether methanol is the solvent or not, it is possible to tune the products towards mesitylene or *p*-xylene, with good selectivities (respectively 100 and 80%). A reference test without catalyst did not provide any detectable amount of alkylation product ascertaining that the observed activity of $\text{mpg-C}_3\text{N}_4$ is not an artifact.

The reaction of formic acid with benzene produced benzaldehyde in quantitative yield. This result could be the basis of a very valuable alternative to the usual benzaldehyde synthesis relying on the oxidation of toluene. Without catalyst, formic acid totally decomposed.

The attempts with molecules bearing nitrogen atoms afforded unpredicted results. Tetramethylammonium bromide yielded 100% of toluene, corresponding to the transfer of one methyl group per ammonium molecule. This reaction is obviously not a sustainable way of alkylating benzene, but it supports our assumption that the catalysis proceeds *via* the activation of the aromatic ring. Indeed,

Table 1 Friedel–Crafts type reactions of benzene with various electrophiles catalysed by $\text{mpg-C}_3\text{N}_4$ ^a

Electrophile	Conversion rate ^b (%)	Products
Methanol	10	Toluene (20%) <i>p</i> -Xylene (80%)
Methanol ^c	20	Mesitylene (100%)
Methanol ^{c,d}	<0.5	—
Ethanol ^c	18	<i>p</i> -Diethylbenzene (100%)
Isopropanol ^c	13	Cumene (100%)
Formic acid	100	Benzaldehyde (100%)
Formic acid ^d	100	Decomposition products of formic acid
Tetramethylammonium bromide	100 ^e	Toluene (100%)
Tetramethylammonium bromide ^d	15 ^e	Toluene (100%)
Urea	20	Benzonitrile
Urea ^d	<0.5	—

^a Reaction conditions: 50 mg of catalyst, 200 mg of the limiting reactant, 5 ml of solvent, at 150 °C for 24 h. ^b The conversion rate was calculated as the molar ratio between the products and the initial amount of limiting reactant. ^c In those cases the alcohol was used as the solvent. ^d Reference tests made without catalyst. ^e In this case the conversion rate was calculated on the basis of one methyl group exchanged per ammonium molecule.

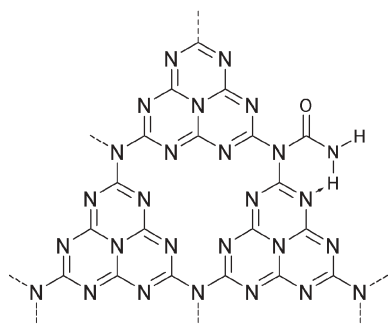


Fig. 3 Possible structure of a ureo- moiety anchored at the surface of **mpg-C₃N₄** detected by FT-IR.

tetramethylammonium is not a Lewis base (and thus cannot be activated in a standard Friedel–Crafts way) and a moderate electrophile (the formal positive charge on nitrogen is in fact distributed on the four methyl groups). A reference test without catalyst yielded only 15% of toluene.

Valorization of urea, which is an abundant and cheap starting molecule, is interesting from an industrial point of view. In our study, the reaction of benzene and urea yielded benzonitrile. This reaction formally implies the addition of urea to benzene followed by the elimination of both a water molecule and an ammonia molecule. The precise reaction path could not be determined. Benzamide, which might have been a possible reaction intermediate, failed to react under similar conditions, indicating that this compound does probably not play any role in the reaction cycle. Interestingly, after a 20 h treatment with urea at 150 °C, **mpg-C₃N₄** features three new peaks in FT-IR compared with the non-urea treated solid, at 1691 cm⁻¹, 1588 cm⁻¹ and 1423 cm⁻¹. These peaks cannot be attributed to possible remaining urea; on the contrary, they are consistent with the formation of ureo-moieties on the surface of our catalyst. Indeed, Lotsch and Schnick recently showed that primary and secondary amines were present at the surface of C₃N₄.²⁸ The later surface species could react with urea to form anchored urea species as depicted in Fig. 3. In this case **mpg-C₃N₄** could be able to activate both the benzene and urea.

In this contribution we have shown that **mpg-C₃N₄** is a valuable Lewis base catalyst which enables rather unusual aromatic substitution reactions of a generalized Friedel–Crafts type. This metal-free catalyst not only allows the use of sustainable

alkylation agents such as alcohols or acids, it also shows an unpredicted reactivity towards urea and quaternary ammonium compounds. Further experimental and theoretical data are needed to provide a detailed mechanism for the observed activation of benzene and the collecting work therefore is still in progress.

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